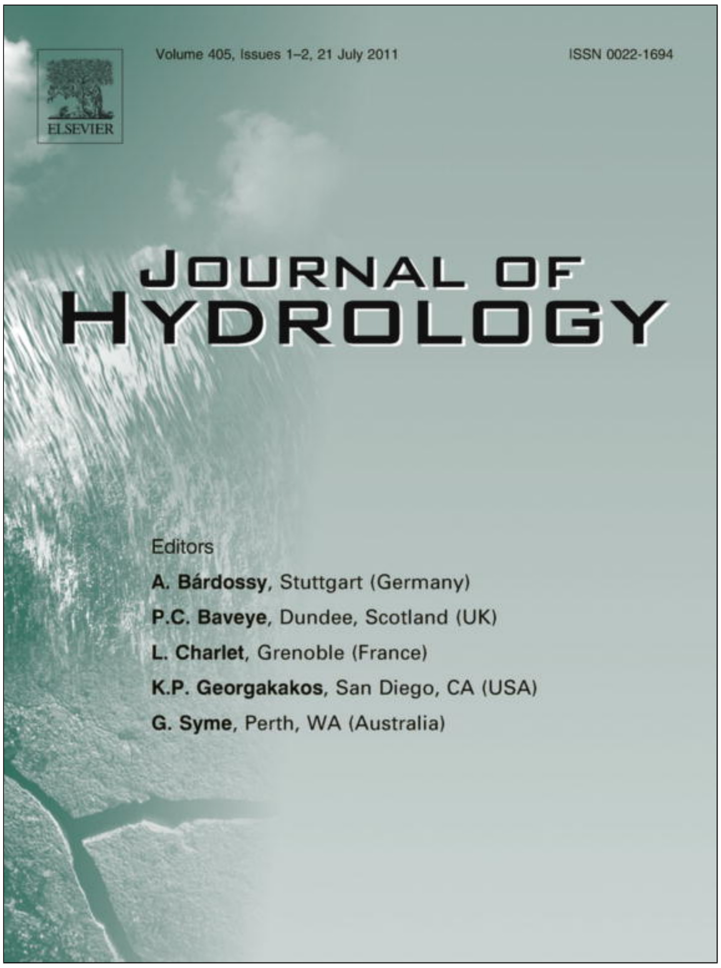
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Southern Patagonia's Perito Moreno Glacier, Lake Argentino, and Santa Cruz River hydrological system: An overview

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SUMMARY

An overview of the hydrological data from Patagonia's Perito Moreno Glacier–Lake Argentino- and Santa Cruz River system reinforces our previous assertion that the El Niño Southern Oscillation (ENSO) and the Antarctic Oscillation (AAO) are teleconnected with the rupture sequence when the glacier's snout harmonically dams (during certain interannual periods) the Rico branch of Lake Argentino. It is clear, however, that the incidence of interannual climatic anomalies is not uniform in time and appears embedded in decadal or quasi bidecadal periods of relative damming inactivity. The use of nonparametric tests shows that there are no significant positive trends in the river's annual discharge with the only exception of the yearly snowmelt/ice melt periods (September–October), when riverine flow appears to increase with statistical significance. The question of the glacier's stability looks like a complex multivariate process, although we do not rule out the occasional role of ENSO/AAO. A longer hydrological data series (i.e., 100 years) would prove useful in casting some light on this intriguing process, surely accounting for the glacier's response time.

1. Introduction

Glaciers worldwide are vitally important for the sustainability of good quality water resources to supply the increasing demand for household, industrial, and agricultural uses. In equatorial, tropical, and subtropical latitudes, such role reaches special significance. Increased ice melt determines an amplified riverine and ground water supply in the short term but would result in decreased availability in a long-term framework. Therefore, abundant scientific literature has repeatedly argued during the relatively recent past that glaciers are robust indicators of long-term climatic change (e.g., Bradley et al., 2006). The significant retreat of many glaciers in different parts of the world during the second half of the 19th, all the 20th century, and the ongoing initial decade of the 21st, has supplied the necessary evidence; examples of such process are found everywhere, in the Northern (e.g., Hirabayashi et al., 2010; Khromova et al., 2006; Kutusov and Shahgedanova, 2009; Shangguan et al., 2009; Yuanqing et al., 2008) as well as in the Southern (e.g., Anderson et al., 2008; Gordon et al., 2008; Masiokas et al., 2008; Rivera et al., 2007; Rivera and Casassa, 2004; Viulle et al., 2008) hemispheres. For example, Lopez et al. (2010) have studied length fluctuations of 72 glaciers between 1945 and 2005 in the Northern Patagonia Icefield (NPI) and Southern Patagonia Icefield (SPI), and in the Darwin Cordillera Icefield (DCI). The majority of the studied glaciers have retreated significantly, with maximum values of 12.2 km for Marinelli Glacier in the DCI, 11.6 km for O'Higgins Glacier in the SPI, and 5.7 km for San Rafael Glacier in the NPI.

There are, however, a much smaller number of glaciers that, in contrast, appear as stable or even show a tendency to advance. The Perito Moreno (a.k.a. Moreno), for instance, is one of only three glaciers in the SPI that have not retreated during the last 50 years (Ciappa et al., 2010). The Pio XI Glacier (e.g., Rivera and Casassa, 1999) in the Chilean Andes, or Hubbard Glacier in Alaska (http://ak.water.usgs.gov/glaciology/hubbard/) are other valid examples. The Moreno Glacier in southern Patagonia has shown what appears to be a relatively stable situation during the 20th century and the first decade of the 21st (i.e., the record period). Lopez et al. (2010), nonetheless, have determined an advancement for the Moreno Glacier of 0.64 km between 1945 and 2005, much less than de Pio XI Glacier that has advanced 8.3 km during the same period (Lopez et al., 2010). Besides appearing immune to global climate change, the Moreno Glacier is special in the sense that the ice terminus periodically dams the Rico branch (i.e., a smaller branch of proglacial Lake Argentino, which is a relict of Pleistocene glaciations). Mainly due to this peculiar behavior, several authors have examined different aspects of the Moreno Glacier: Aniya and Skvarca (1992), Casassa et al. (2007), Ciappa et al. (2010), Lopez

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et al. (2010), Rott et al .(1998), Skvarca et al. (2004), Stuefer et al. (2007), Takeuchi et al. (1996, 1999), Warren (1994), and Warren and Aniya (1999), among others.

Several years ago, Depetris and Pasquini (2000) explored the hydrological behavior of the Santa Cruz River (which is the lowermost member of the system), inferring through its flood dynamics the occasional quasi harmonic periodicity of the closure-rupture sequence. Moreover, it was later found that several other Patagonian lakes located north of ∼50°S showed an El Niño Southern Oscillation (ENSO) signature in their deseasonalized water level fluctuations (Pasquini et al., 2008).

In this contribution, we wish to show our expanded insight on the above natural process, supplying an updated overview and our current evaluation on the mechanisms governing the Moreno's closure-rupture sequence, and the connection with Lake Argentino and the Santa Cruz River flow.

2. The characteristics of the Perito Moreno Glacier, Lake Argentino, and the Santa Cruz River

The glacier (Fig. 1) is located in the SPI (49° to 51°S), which occupies 13,000 km^2 along the Chile-Argentina Andean border and has about 48 outlet glaciers – among them, the Moreno – that calve into fjords on the Pacific side, and into lakes on the eastern side of the Andes (e.g., Warren and Aniya, 1999).

According to several authors (e.g., Aniya and Skvarca, 1992; Stuefer et al., 2007), the Moreno Glacier is about 30 km-long, and reaches a width of about 4 km in the valley. The location of the snout is approximately at 50° 28′S and 73° 02′W (Fig. 1). The glacier covers an area of 259 km^2 and extends from the continental divide (Pietrobelli peak, 2950 m a.s.l.) down to Lake Argentino (∼187 m a.s.l.). Hence, the mean surface slope is approximately 100 m km^{-1}. The snout ends in calving cliffs with heights of 50–80 m (Rott et al., 1998). Warren and Aniya (1999) have listed several parameters related to calving: ice velocity, 535 m y^{-1} (mostly centerline values); calving rate, 510 m y^{-1}; calving flux, 0.5–1.0 km^3 y^{-1}; water temperature, 5.5–7.6 °C; and ablation rate, 5.6 cm w.e.d^{-1}.

The ablation zone below an estimated equilibrium line altitude (ELA) of 1160 m a.s.l. covers about 74 km^2. Conversely, the accumulation zone covers an area of 180 km^2 and, therefore, the accumulation area ratio (AAR) is 0.71, which denotes a steady state for the Moreno Glacier (e.g., Warren, 1994; Stuefer et al., 2007) (Fig. 2). An ice thickening trend in the ablation area, which increased significantly (more than 6 m) between 1999 and 2002, was investigated by Skvarca et al. (2004). These authors concluded that it was most likely not related to a surge, but it could be connected to dynamic causes or a positive mass-balance in the glacier.

The average specific annual net accumulation of the Moreno Glacier was established in 5540 ± 500 mm water equivalent, which is considered one of the highest accumulations worldwide; considering that part of the precipitation is surely lost as runoff, the real average annual precipitation could be of the order of 7000–8000 mm (Rott et al., 1998).

Lake Argentino (Fig. 1) is the following element of the hydrologic system (http://www.hidricosargentina.gov.ar/Indice-argentino.html,

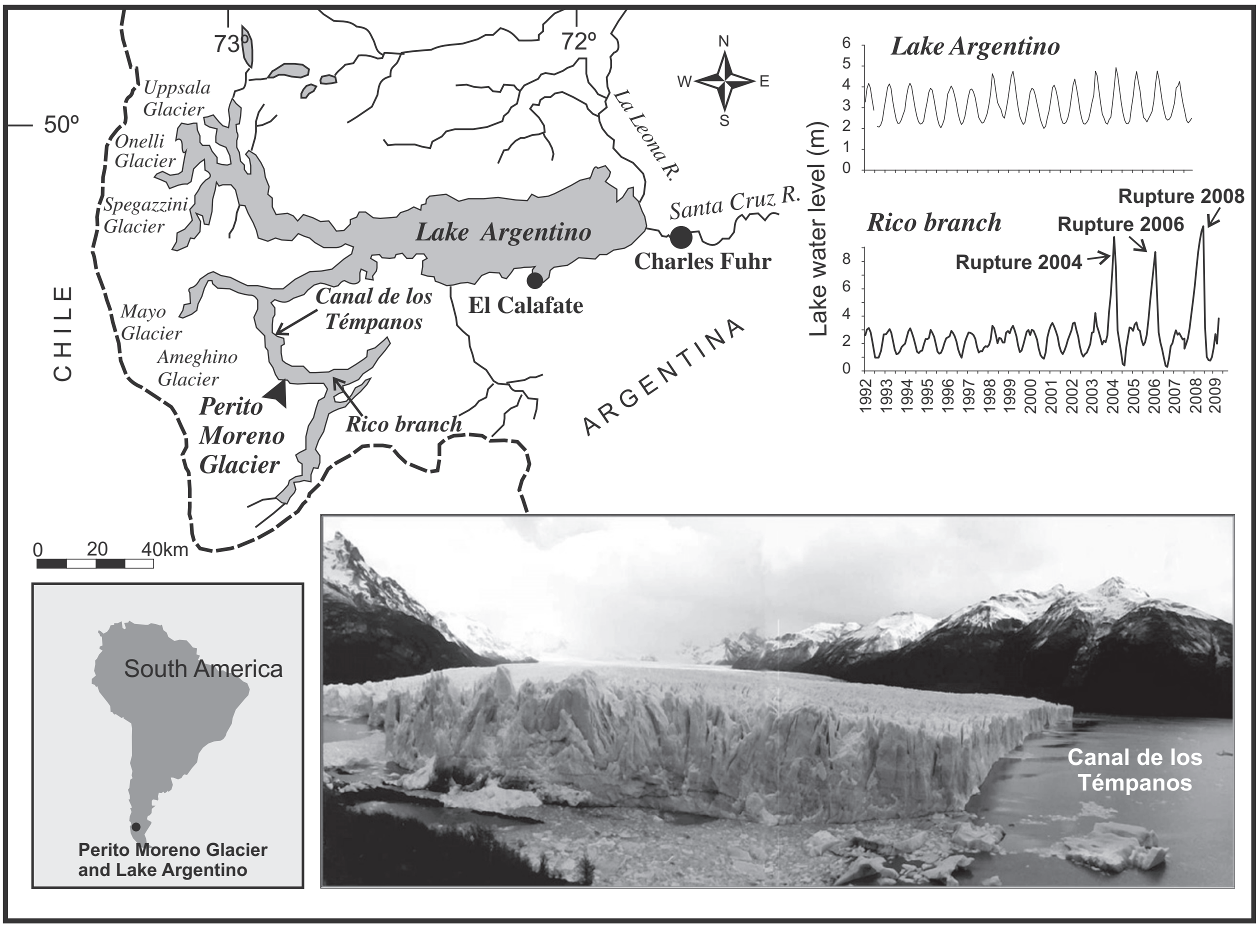

Fig. 1. A picture of the Perito Moreno Glacier terminus, a map of the hydrological system integrated by the glacier, Lake Argentino, and the headwaters of the Santa Cruz River. South America's map (Lower left side) shows the location of the area in the southern Argentine Andes. The inset on the upper right hand corner shows the water level gage height variability (period 1992–2009) at the Rico branch (notice the water level reached behind the ice dam during the last 3 ruptures), and the corresponding modulated level in Lake Argentino.

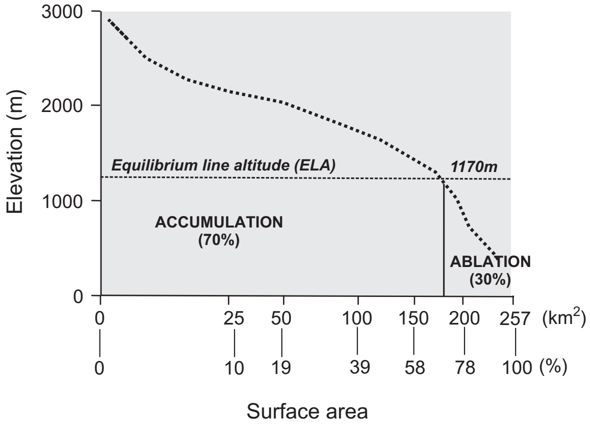

Fig. 2. Moreno Glacier's hypsometric curve. Notice the steepness of the curve where the ELA intersects it (modified from Aniya and Skvarca, 1992).

~50°S 73°W, 187 m a.s.l.). This ultra-oligotrophic lake is among the largest lakes in Patagonia and also is the southernmost lake of the long chain of Patagonian proglacial lakes (i.e., the geomorphologic result of 26 glacial–interglacial cycles that occurred during the Quaternary, Pasquini et al., 2008 and references therein) bordering the austral Andes along the eastern seaboard. It has a mean depth of 150 m although it reaches about 500 m in certain areas. Its surface area is close to 1500 km^2 and its volume has been estimated in about 220 km^3. The lake's drainage basin area is about 5000 km^2 and several glaciers calve on the Argentino or the Viedma lakes (e.g., Perito Moreno, Viedma, Ameghino, Uppsala, Mayo, Onelli). The Argentino is also fed by several streams and rivers (e.g., La Leona, Centinela, Mitre). The Santa Cruz River is the only outlet of Lake Argentino, after receiving the discharge of the nearby La Leona River, the outlet of Lake Viedma, which in this manner is connected with the Argentino. In an earlier contribution (Depetris and Pasquini, 2000), we have shown that discharge anomalies (i.e., the deseasonalized series) in La Leona and in the Santa Cruz River, are not significantly correlated.

The Santa Cruz River is the end member of the Moreno–Lake Argentino–Santa Cruz River hydrological network. It was explored to a certain extent (they did not reach the lake) by Charles Darwin, Robert FitzRoy, and part of the crew of the *HMS Beagle*, in April of 1834, during her second trip to Patagonia. It is 385 km long, crosses eastward the Patagonian plateau, and delivers its noteworthy mean discharge (about 700 $m^3 s^{-1}$; its runoff is about 1500 mm y^{-1}) in a 2 km-wide estuary (shared with Chico River), in the SW Atlantic Ocean. Its drainage basin has a surface area of about 24,000 km^2; its mean water-surface slope is about 0.48 m km^{-1}; the mean maximum water discharge (~1200 $m^3 s^{-1}$) occurs in March and the mean minimum flow (~300 $m^3 s^{-1}$) in September. Its mean annual water yield is about 29 l s^{-1} km^{-2} of deep-blue water, whereas its mean total suspended sediment concentration is about 23 mg l^{-1}(roughly fluctuating between 11 and 33 mg l^{-1} in al least 10 different determinations). Finally, its mean total dissolved solids concentration is about 100 mg l^{-1} (near the mouth, oscillating between 76 and 137 mg l^{-1}, in at least 10 different determinations) (Depetris et al., 2005).

3. Data source and methods

The time series of monthly mean Santa Cruz River discharge and the gage heights at Lake Argentino and the Rico branch were obtained from Argentina's Subsecretaría de Recursos Hídricos (http://www.obraspublicas.gov.ar/hidricos/). The problem of some missing data was solved by using historic means.

To assess the significance of discharge trends in river data, we employed the Mann–Kendall test -also known as Kendall's tau- (Mann, 1945; Kendall, 1975) to test trends on mean annual discharge data, and the seasonal Kendall test (Hirsch et al., 1982) to examine monthly trends. Both, are non-parametric tools to detect monotone trends in time series (e.g., Burn and Hag Elnur, 2002; Yue et al., 2002). The seasonal Kendall test has been selected as one of the most robust techniques available to detect and estimate linear trends in environmental data (Hess et al., 2001).

To investigate periodicities in river discharge data, we have used deseasonalized monthly mean series obtained by subtracting the monthly historical means from monthly means. Two spectral procedures were applied on deseasonalized data series: classical Fourier analysis and continuous wavelet transform (CWT). The classical Fourier transform uses sine and cosine base functions that have infinite span and are globally uniform in time and only reveals what spectral component is present in the signal (Lau and Weng, 1995). It does not contain any time dependence of the periodicity. In this case we applied Fourier analysis to determine the squared coherency between hydrological data and climatic indices.

The CWT examines a time series using generalized local base functions (mother wavelets) that are stretched and translated with a resolution in both frequency and time. This tool offers several advantages in comparison with traditional Fourier analysis because it provides a time-scale localization of a signal. Thus, wavelet transform reveals some aspects that other spectral analyses miss, such as trends, breakdown points, and discontinuities (Nakkem, 1999). The literature offers numerous reviews on the theoretical aspects of CWT and Fourier analysis (e.g.; Labat, 2005; Lau and Weng, 1995; Torrence and Compo, 1998).

We have also applied power analysis – frequency range, a special option that offers the CWT. It computes the power of the continuous wavelet spectrum across time for a specified frequency band by integrating the interpolated wavelet spectrum surface and, hence, allows obtaining detailed information on the power of a specific periodicity across time.

4. Dynamics of the ice dam rupture sequence

As stated above, the Moreno Glacier sporadically dams the Rico branch (i.e., a secondary branch of Lake Argentino) and causes the lake water level (in the Rico branch) to rise several meters above the most frequent level until the ice dam, usually between 15 months and 2 or 3 years after the closure, spectacularly collapses, frequently in March (i.e., the end of austral summer), thus producing a water outburst, a flood wave that, although modulated by the size of the lake, frequently produces a discernible signal in the discharge regime of the Santa Cruz River, which drains Lake Argentino towards the SW Atlantic Ocean (Fig. 1).

For example, in December 2007 the channel connecting the Rico branch and the Canal de los Témpanos, in proglacial Lake Argentino (Fig. 1), was ice-dammed by the Moreno Glacier for the third time since the beginning of the 21st century. On July 9th, 2008, a portion of the Perito Moreno Glacier's snout (Fig. 1) spectacularly collapsed, like in preceding occasions, in an awesome event that attracted the attention of international media. This would have been a typical damming-collapsing event if it weren't for the delayed collapsing of the ice dam (i.e., it occurred in winter time). Such an overdue rupture resulted in a larger water volume stored behind the ice dam. For many years now, such an extraordinary natural phenomenon made the glacier a widely-known geographical feature.

A series of damming-rupture episodes occurred in the Moreno Glacier (Del Valle et al., 1995). The first documented collapse of the ice dam occurred in the Moreno in 1917. After a period of noticeable inactivity, the damming-rupture sequence got underway in 1934, with ruptures in 1935, 1940, 1942, 1947, 1952, and 1953. Since the Santa Cruz River discharge is being recorded (i.e., late 1955), the ice dam fell down and produced outburst floods in 1956. After another period of inactivity, it resumed the rupture sequence in 1966. Additional snout breakdowns occurred in 1970, 1972, 1975, 1977, 1980, 1984, and 1988. An incipient damming appears to have occurred in 1990. Then, the glacier blocked the Rico Channel and the ice dam collapsed again in 2004, 2006, and – as stated above – in 2008. Anomalous discharge peaks (i.e., apparently not connected with sudden break floods) in the Santa Cruz occurred in 1960 and 1963. Therefore, most outstanding positive departures from mean discharge in the Santa Cruz River appear connected to glacier-triggered flooding.

Initially, the deseasonalized monthly discharge record of the Santa Cruz River for the period 1956–1994 was analyzed by means of power spectrum analysis (Depetris and Pasquini, 2000). As a tool to establish statistically significant periodicities, we used the Fourier harmonic procedure (with white noise, i.e., the signal contains equal power within a fixed bandwidth at any center frequency).

The resulting periodogram revealed a pronounced spectral peak in the 33- to 36-month period range and secondary peaks at 42- and 58-month periods. All these peaks lay within the $p < 0.05$ line (Depetris and Pasquini, 2000). At the time, we concluded that the strongest peak was probably due to the anomalous latitudinal shifting of the subtropical anticyclones that, when residing further north than usual, middle and high latitude areas receive abnormally-high precipitation (Depetris and Pasquini, 2000, and references therein). The remaining secondary peaks (i.e., 42- and 58-month periods) were attributed to the influence of ENSO inasmuch they were significantly ($p < 0.05$) coherent with the multivariate ENSO index (MEI).

Fig. 3 shows that, Lake Argentino water gage heights and Santa Cruz River discharge series, are significantly correlated ($r^2 = 0.98$, $p < 0.001$) for the available record period (1992–2009). Furthermore, the linear regression equation indicates that, on the average, a water gage level of, for example, 3 m in Lake Argentino, determines at the Santa Cruz River (Charles Fuhr gagging station), a discharge of about 650 $m^3\ s^{-1}$.

It is not surprising then that damming-rupture events (Fig. 4) tend to affect the water level gage height at Lake Argentino (Fig. 4b) and, sometimes, it does it in an uneven manner (e.g., the 2008–2009 damming-rupture event determined – as mentioned before – a more prominent water level increase in the deseasonalized series for Lake Argentino than the two previous ruptures) (Fig. 4b). It follows that this affects the deseasonalized discharge series at the Charles Fuhr gagging station in the Santa Cruz (Fig. 4c). It is clear, however, that some discharge extremes are due to occasional events of excessive atmospheric precipitation.

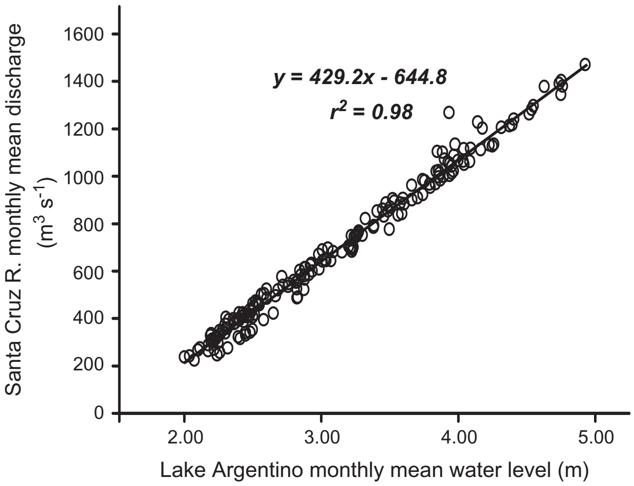

Fig. 3. Statistically significant linear correlation ($p < 0.001$) between Lake Argentino water level gage height and Santa Cruz River monthly mean discharges at the Charles Fuhr gagging station (Fig. 1).

The Mann–Kendall test was also employed in this case to asses again –with the longer data series (period 1956–2009, Fig. 5a and b) – the likelihood of monotonic trends in the Santa Cruz River annual discharge series. As was recognized before (Pasquini and Depetris, 2007) the Santa Cruz deseasonalized discharge series does not show a significant decreasing or increasing trend. However, the seasonal Kendall test (i.e., that allows to identify anomalous increasing trends in specific months) showed, as was also established before (Pasquini and Depetris, 2007), some significant results (Table 1). Due to the influence of glacier melt water, the Santa Cruz is the only river in Patagonia that presents a significant increasing trend in September ($p < 0.01$) and October ($p < 0.05$). Earlier results obtained with the shorter data series extended this characteristic until December (Pasquini and Depetris, 2007). September is, precisely, the time of the lowest discharge in the Santa Cruz, almost exclusively supported by melt water.

The longer Santa Cruz River hydrological time series (Fig. 5a) was also used to assess discernible periodicities. In this opportunity the discharge time series at the Charles Fuhr gagging station was employed for the period 1956–2009 as well as its deseasonalized version (Fig. 5b). Both series show outstanding peaks (negative or positive in the case of the deseasonalized series) that mostly correspond to rupture events. The deseasonalized time series clearly shows that there are both, periods with frequent damming-rupture sequence (i.e., interannual frequency) as well as extended periods (i.e., decadal or quasi-bidecadal) without any significant closure-rupture event, as the one recorded between 1988 and 2004.

As a first step in this revisit, we examined the periodicities of the new, longer series, by means of the real part of the continuous Morlet wavelet spectrum of the Santa Cruz River deseasonalized monthly mean discharge (Fig. 6a). Also included in the figure (Fig. 6b) is the wavelet power-frequency range for the 2–5 year frequency band that clearly shows the increased integrated power during the period when damming-rupture events occurred frequently (i.e., late 1960s until late 1970s). The most recent events (2004, 2006, and 2008) appear to determine and incipient raise in power and obviously leads to the idea that damming-rupture events (i.e., reflected in the anomalous river discharge) have periods of frequent occurrence embedded in longer periods of relative inactivity. Fig. 6a, moreover, shows that time lapses with relatively uniform frequencies (i.e., ~40 months and ~34 months) are also uneven in their relative power, leading us to believe that, if such events are mainly ENSO-caused (as we proposed earlier, Depetris and Pasquini, 2000), such a relationship changes in time.

Let us now concentrate on the statistical picture of the rupture events and leave aside, for the moment, the mechanism that determines the glacier's apparent stability. It must be kept in mind that rupture events are largely determined by the rate of accumulating water behind the ice dam, at the Rico branch. The squared coherence attained between the newer, expanded Santa Cruz River deseasonalized data series and the Southern Oscillation Index (SOI) (Fig. 7a), is somewhat different from the one published previously (Depetris and Pasquini, 2000) and now it shows only one statistically significant peak (period of 42.7-month) that is clearly coherent with the SOI periodicity in the Pacific. This result of the harmonic analysis would reinforce the suggestion that there is a significant linkage between ENSO occurrences in the Pacific and rupture events in the Perito Moreno Glacier. The earlier suggestion (Depetris and Pasquini, 2000) that, additionally, there appeared to

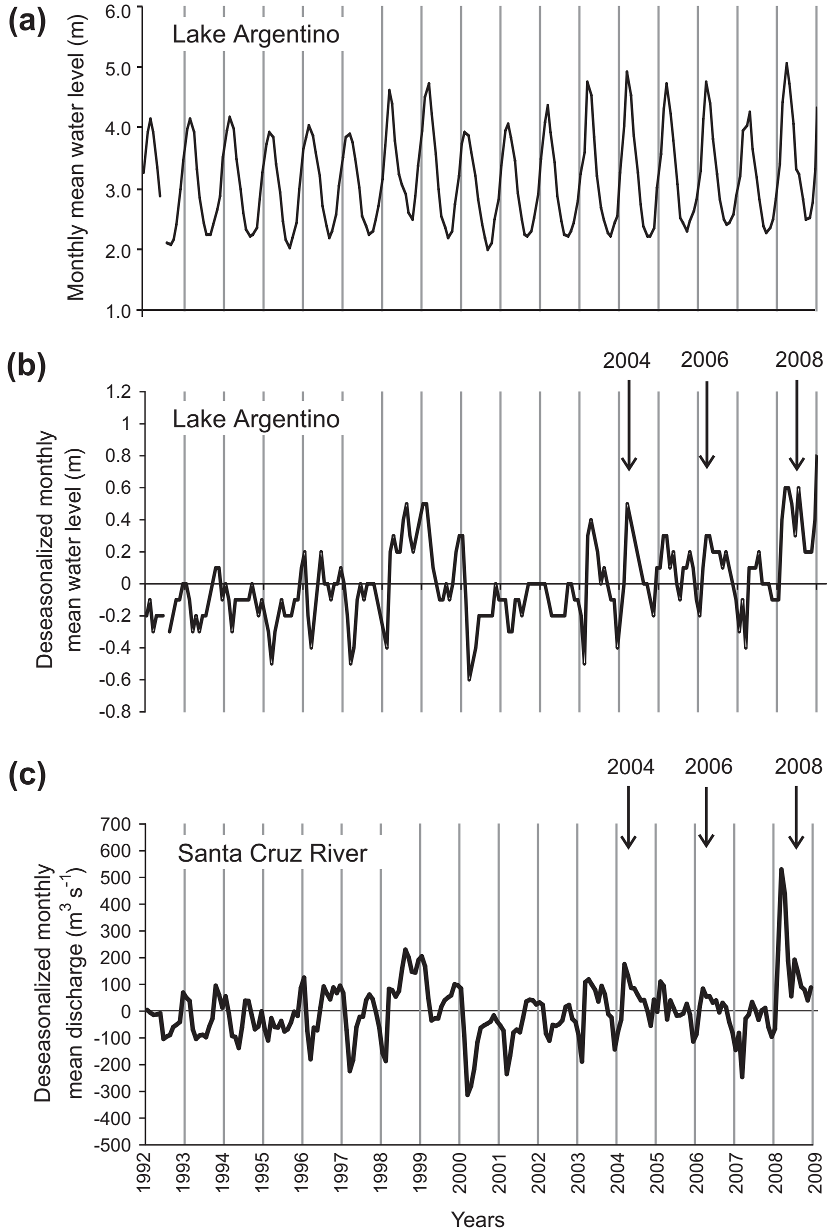

Fig. 4. (a) Monthly mean water level variability (period 1992–2009) at Lake Argentino; (b) Same as (a) but deseasonalized data; the last 3 damming-rupture events in the Moreno Glacier are indicated; (c) Deseasonalized monthly mean discharge for the Santa Cruz River at Charles Fuhr gagging station; the last 3 damming-rupture events are indicated. See the text for an explanation of the water height reached by the 2008 rupture event.

be a liaison with the latitudinal shifting of the subtropical anticyclones that, when residing further north than usual, middle and high latitude areas receive heavy precipitation, is no longer significant in the extended data series.

On the other hand, the effect of the Antarctic Oscillation (AAO) on Patagonia's high latitude climate has been proposed in several instances (e.g., Jones and Widmann, 2003). However, the individual forcing effect of ENSO and AAO on the water level of Lake Argentino and the subsequent discharge of Santa Cruz River is difficult to be recognized because – as was recently established by Bertler et al., 2006 – they appear to be correlated and this turns almost indistinguishable the significance of each mechanism. At any rate, the effect of the ENSO/AAO is discernible in Patagonian lakes (Pasquini et al., 2008) although it does not seem to induce a positive or negative trend in their respective water levels.

The coherence of AAO and the deseasonalized Santa Cruz River discharge was also verified (Fig. 7b). A significant ($p < 0.05$) squared coherency was obtained with a quasi decadal periodicity (~85-month) which, incidentally, is often evident in ENSO-affected systems, like the Paraná River (e.g., Pasquini and Depetris, 2007).

A number of authors have cited our work, in which it was proposed that Moreno's snout rupture dynamics is somehow connected with ENSO events: e.g., Ciappa et al. (2010), Crétaux and Birkett (2006), Fitzharris et al. (2007), Kastner et al. (2010), Moore et al. (2009), Viles and Goudie (2003), and Zolitschka et al. (2006). Schneider and Gies (2004), studied the effects of ENSO on the southernmost precipitation at 53°S revealed by the reanalysis project (NNR) and claimed that their results were opposed to our proposal that El Niño had some influence on the snout rupture sequence at the Perito Moreno Glacier. It must be remembered, however, that the Moreno Glacier is located at around 50°S and that it is situated most likely in a transition zone, where the connection with El Niño – clearly discernible north of 45°S – is sometimes statistically significant, and sometime it is not, as the

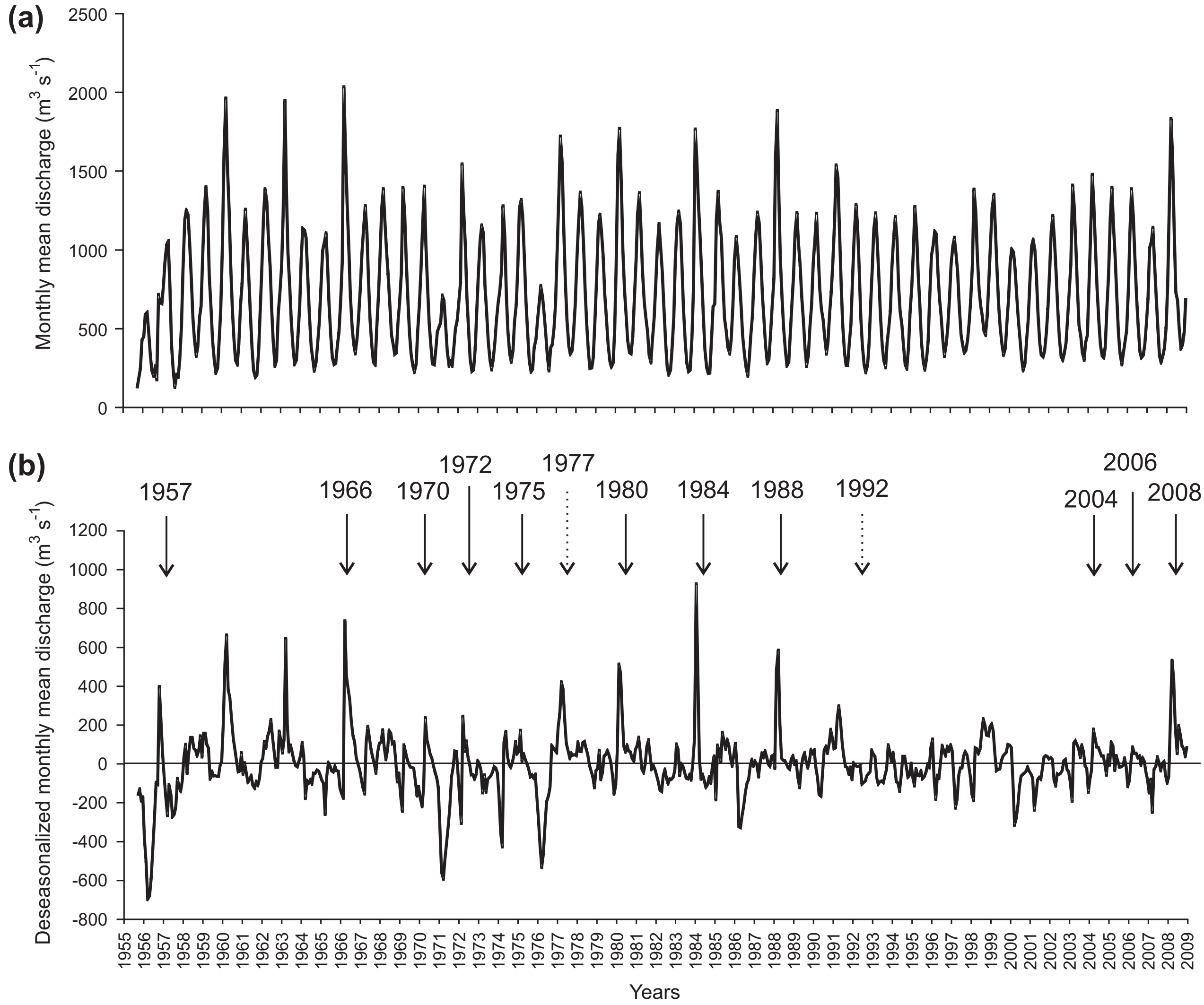

Fig. 5. (a) Monthly mean Santa Cruz River discharge series (1955–2009) determined at Charles Fuhr gagging station; (b) Same as (a) but deseasonalized discharge data; known damming-rupture episodes are indicated with solid arrows (dotted arrows are incomplete damming episodes).

Table 1
Seasonal-Kendall test for the Santa Cruz River monthly mean discharge (record period: 1956–2009). Months with statistically significant trend are indicated in bold.

Month	τ coefficient	p value
January	0.13	0.448
February	0.09	0.463
March	0.38	0.350
April	−0.59	0.277
May	−0.33	0.367
June	−0.46	0.322
July	0.66	0.252
August	1.40	0.081
September	2.41	**0.008**
October	2.32	**0.010**
November	0.52	0.300
December	0.45	0.325
All	0.92	0.177

continuous Morlet wavelet spectrum suggests (Fig. 6a and b). Further, our current analysis also proposes that the AAO surely plays a role as well and, hence, the glacier's rupture sequence is not a pure signature. Moreover, it is worthy citing the statement of Díaz et al. (2001): "...it appears that the strongest signals may occur in places and times where the forcing of ENSO and longer term features of SST variability (...) reinforces climatological aspects of the annual cycle". Most Moreno's ice dams have collapsed in March (i.e., end of austral summer), where maximum atmospheric precipitation is recorded.

5. The question of Moreno's stability

What is so special about these sporadic events, besides the occasional breathtaking sight of gigantic ice blocks plunging into the cold waters of Lake Argentino? Firstly, it is sustaining evidence that the Moreno Glacier is a stable glacier, with an oscillatory terminus, when most glaciers worldwide, due to the current global warm spell, are in open retreat (e.g., according to Skvarca et al. (2003) the retreating rate of the nearby Uppsala Glacier fluctuates between 70 and 150 m y^{-1}). From the previous section we can conclude that the ice-dam collapsing sequence is independent of the mechanisms that govern the glacier's oscillatory behavior, which occasionally blocks the channel linking the Rico branch with the Los Témpanos channel.

In our earlier treatment of this subject (Depetris and Pasquini, 2000) we interpreted that ENSO events in the Pacific not only had influence in the rupture mechanism but also in the advancement of the glacier and the damming of the Rico Branch. In what

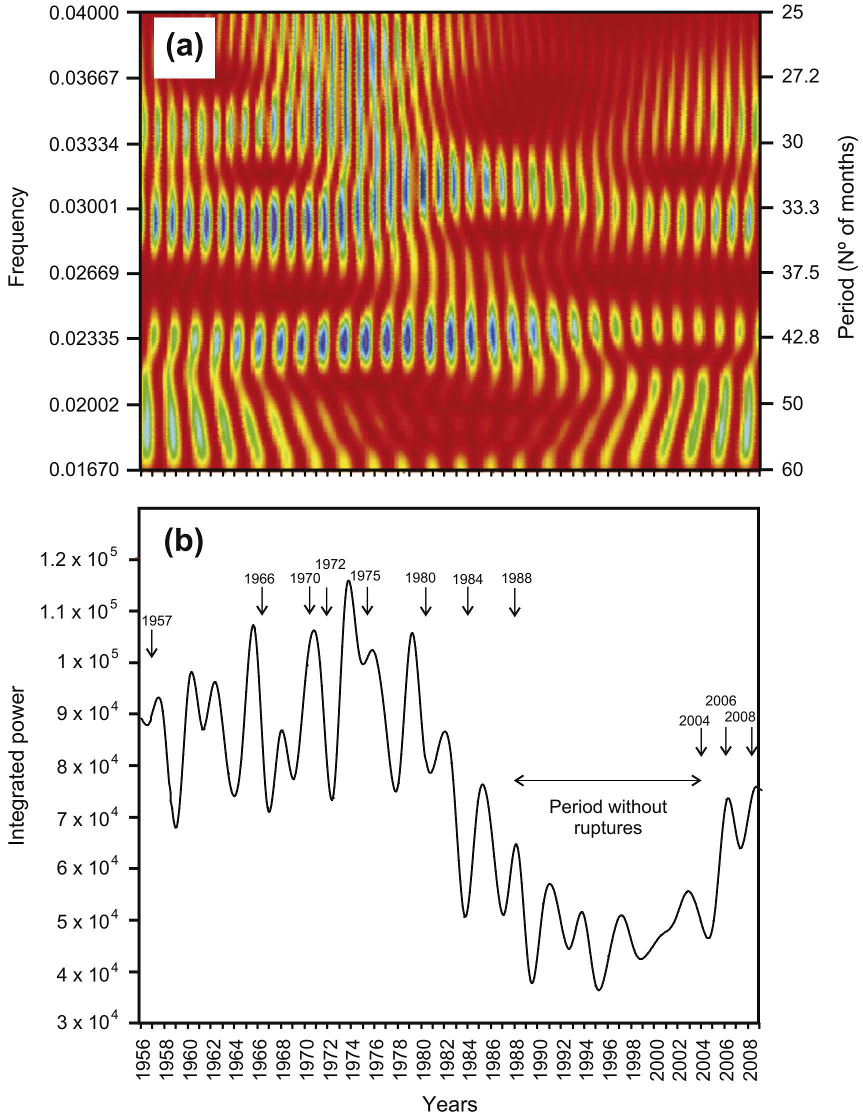

Fig. 6. (a) Real part of the continuous Morlet wavelet spectrum of the Santa Cruz River deseasonalized monthly mean discharge; dark colors represent high power; (b) Wavelet power-frequency range for the 2–5 year frequency band that shows the increased integrated power during the period when damming-rupture events occurred frequently; known damming-rupture events are indicated. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

we considered a typical episode (recorded by Argentina's Parques Nacionales), there was an El Niño event in 1939, and the glacier dammed Lake Argentino's Rico branch. The water level in the southern branch started to increase. In 1941, another El Niño occurred in the Equatorial Pacific and the water in the Rico branch reached a level of 7.4 m. The water level reached 13.4 m in February and over 17 m in March 1942. On March 21, 1942, the ice-dam collapsed and an outburst flood took place (Depetris and Pasquini, 2000). The influence of ENSO events on glacier dynamics has been recognized in tropical (e.g., Jomelli et al., 2009) as well as in subtropical or even temperate glaciers (e.g., Leiva, 1999). Whenever ENSO occurrences (i.e., El Niño or La Niña) promote snow accumulation or dry conditions, the consequences are, sooner or later, discernible in the functioning of some glaciers.

This mechanism, however is in contradiction with the generally accepted rule that the response time (i.e., a measure of the time taken for a glacier to adjust its geometry to a climate change, Raper and Braithwaite, 2009, and references therein) usually takes decades or even centuries. In general, larger glaciers have a larger response time, whereas smaller, steep alpine glaciers respond more quickly, typically a few years. Franz Josef and Fox glaciers in the Southern Alps of New Zealand are exceptionally responsive to small changes. They are among the most sensitive glaciers and their fluctuating terminus locations supply a detailed summary of climate fluctuations.

There is a question that immediately arises when the damming events are considered: which is the mechanism that determines such behavior? In our view, there are several significant factors whose combined effect would partly explain not only the incidence of ENSO or AAO in maintaining the ice dam collapsing sequence, but also the glacier's stability: (a) the maximum height of southern Patagonia's cordillera shows a clear decreasing trend from ~47°S southward, with top heights placed well below 3000 m a.s.l. at ~50°S (Montgomery et al., 2001; Pasquini et al., 2008), thus allowing the penetration of westerly-driven Pacific moisture; (b) the mean specific annual net accumulation of Moreno Glacier, with 5540 ± 500 mm water equivalent, is among the highest accumulation rates worldwide (Rott et al., 1998); (c) in the Moreno Glacier, the altitude of the snow line at the end of the austral summer or ELA (estimated in 1170 m), thus determining an AAR of ~0.70

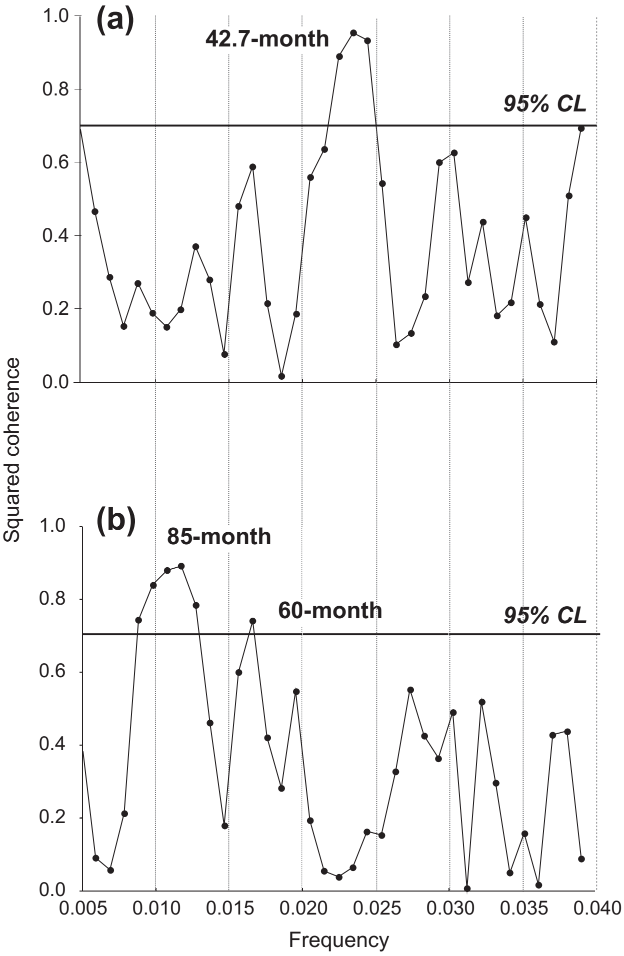

Fig. 7. (a) Squared coherence (Fourier harmonic analysis) between the Santa Cruz River deseasonalized discharge data and the Southern Oscillation Index (SOI); the horizontal line shows the 95% confidence level; (b) Same as (a) but with the Antarctic Oscillation index (AAO).

(Stuefer et al., 2007), which in turn means that the Moreno accumulates snow on about 70% of its surface area, and finally; (d) Moreno's steep hypsometric curve means that significant changes in the ELA result in relatively minor changes in the accumulation area. At any rate, more research is needed to fully understand the current stability of the Perito Moreno Glacier. A longer hydrological data series (i.e., at least 100 years) would allow (through cross-correlation, for example) to establish if a given ENSO (or AAO) event is connected with a damming-rupture episode that accounts for the glacier's response time, mainly because we suppose it would be of the order of 30–60 years.

6. Concluding comments

The integrated Patagonia's hydrological system that includes the Perito Moreno Glacier, Lake Argentino, and the Santa Cruz River that delivers about 22×10^9 m^3 y^{-1} to the SW Atlantic is typical of high latitudes in the sense that it is fed by snow- and rain-fall, snow and ice melt water and, possibly, ground water. It has, however, an uncommon aspect because it is affected by the peculiar behavior of the Moreno Glacier, whose terminus dams a side arm of Lake Argentino, the Rico branch. At certain time lapses, the terminus dams the Argentino's side branch with quasi harmonic regularity. The ice dam eventually collapses and generates a flood wave that is modulated in Lake Argentino but is finally transmitted to the Santa Cruz River. In an earlier contribution (Depetris and Pasquini, 2000) we proposed that such mechanism functioned under the influence of some climate anomalies such as ENSO and the location of the Pacific anticyclone. In this paper, by means of a longer data series, we propose that the signal of ENSO or the AAO is discernible – through statistical techniques – in the rupture sequence although this does not happen always with the same periodicity and/or intensity.

Why the Moreno Glacier is not retreating when all neighboring glacier are? We feel that there are several aspects, some mentioned above, that play a role. We also feel that the ENSO and/or AAO may be important factors in the process. However, as it was stated above, the available hydrological data series is not long enough to fully test this hypothesis.

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